NUMERICAL MODELING OF ICE-STRUCTURE INTERACTION

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1. INTRODUCTION

OBJECTIVE OF PROPOSED WORK

The objective of this project is to systematically investigate using numerical models the mechanics of deformation and progressive failure in ice for the purpose of predicting global forces and local pressures on offshore structures proposed for deployment in the Arctic. The focus is on ice sheets interacting with rigid cylindrical indenters. The project involves the following three major areas of study:

1. Development of constitutive models to characterize the mechanical behavior of sea ice.
2. Development of finite element methods of analysis to account for the simultaneous occurrence of viscous (rate dependent) and fracture behavior in ice, and time varying contact between ice and structure.
3. Numerical solution of ice-structure interaction processes for selected ice features and structural configurations to predict global forces and local pressures.

BACKGROUND

As much as 30-40 percent of the U.S. undiscovered hydrocarbon recoverable reserves, comparable in magnitude to those of the Persian Gulf, are estimated to lie in the Arctic. The extraction of these resources in an economical and safe manner poses many technical challenges to offshore engineering. At the root of these problems is the severe environment created by perennial ice features that impart global forces and local pressures on structures which are several times greater than those from waves in non-Arctic environments. Typically, two levels of ice loading are considered for design purposes. Global ice loads govern the overall structural geometry and dimensions as well as the foundation design, while local ice pressures are likely to dictate wall thicknesses and local framing, and may well govern structural cost.

Most of the emphasis in research has been on predicting global forces. Only during recent years, as the focus changed from overall feasibility to preliminary and detailed design, has the importance of local pressures emerged. It is widely recognized that significant uncertainties exist in the ice load models in use today and that some design loads may be overestimated by an order of magntidue. Research is necessary to quantify the uncertainties in ice loads and to develop improved load prediction models for the safe and economical design of structures.

Uncertainties in existing ice load models arise primarily from five sources:

- Incomplete modeling of the mechanical behavior of ice, including temperature and fracture effects.
- Empiricism in existing theoretical models resulting from the use of approximate analysis mdethods.
- Inadequate modeling of the contact forces at the ice-structure interface.
- Neglecting the effect of scale/size on material strength.
- Not accounting for the finiteness of environmental and other forces driving the ice features.

In order to quantify these uncertainties and to better predict global and local ice loads, numerical models are necessary for computer simulation of ice-structure interaction processes. In contrast to analytical methods, such models can realistically simulate the interaction accounting for spatial-temporal variability in the mechanical behavior of ice and for multiple modes of failure in ice.

The complexity of sea ice behavior is due mainly to:

- Strong dependence on rate of loading, which is spatially and temporally variable in ice features.
- Simultaneous occurrence of ductile, strain-softening, and brittle modes of deformation.
- Pressure sensitivity leading to different strengths in compression and tension (at moderate-to-high rates of loading) and to melting point depression.
- Material anisotropy leading to strength variation by a factor of three.
- Strong dependence on temperature, varying in first year ice from melting point at the water interface to perhaps -50°F at the air interface.
- Strong dependence on internal structure of ice (grain size, fabric, brine volume, salinity, porosity), which is spatially varying particularly in multi-year ice features.

A key aspect in the development of constitutive models is the need for accurate and consistent experimental data on ice, especially to characterize its behavior relating to tensile loading, cyclic loading, multiaxial loading, nucleation and interaction of cracks, material anisotropy, thermal and structural gradients, and fracture toughness. Currently available data is in many cases sufficient to postulate approximate constitutive models.

Numerical simulations can help to establish the importance of more extensive experimentation in quantifying ice-structure interaction processes.

Finite element methods of analysis for simulating ice-structure interaction processes are affected by the following research concerns:

- Rate dependent material behavior with negligible elastic deformation.
- Initiation and propagation of cracks due to fracture.
- Simultaneous occurrence of rate dependent and fracture behavior.
- Adfreeze bond and friction at ice-structure interface.
- Time-varying contact between ice and stucture and between fractured ice features.
- Strain-softening of ice.

STAFFING

Dr. S. Shyam Sunder, Assistant Professor of Civil Engineering, is Principal Investigator for this project while Dr. Jerome J. Connor, Professor of Civil Engineering, is Co-Principal Investigator. In addition, two full-time graduate Research Assistants are participating in this research. They are Mr. S-K Ting, a doctoral student with considerable experience in concrete testing and dynamic behavior of offshore structures (9/1/84 - 8/31/85); Mr. F.S. Chehayeb, a doctoral student whose background is in numerical analysis and finite element methods (9/1/84 -5/31/85); and Mr. Jaideep Ganguly, a master's student with expertise in computational mechanics (6/1/85 - 8/31/85).

2. SUMMARY OF RESEARCH ACTIVITIES

The principal technical developments during this reporting period have been:

(1) The study of sea ice indentation in the creeping mode of deformation.

(2) Initiation of research to study sea ice indentation accounting for fracture behavior.

Specific accomplishments and current research directions are discussed below.

SEA ICE INDENTATION IN THE CREEPING MODE

A study of ice indentation in the creeping mode is important for two reasons: (a) creep is the predominant mode of deformation for artificial islands in the Arctic nearshore region during "breakout" and/or steady indentation conditions occurring in the winter, and (b) stresses, strains, and strainrates within the continuum resulting from creep are necessary to predict the initiation and propagation of cracks when viscous effects influence fracture.

Global and local pressures generated during sea ice indentation in the creeping mode are being studied, accounting for the spatial variation of strainrates. Two methods of analysis are being considered: (a) approximate methods, i.e., upper-bound method and strain path method, and (b) "exact" method based on the finite element method. In both cases, a two-dimensional idealization of the indentation process is considered. In order to provide continuity with previous work, the isotropic, incompressible three-dimensional extension of the uniaxial power-law creep model has been extensively studied. Pressures predicted with this model are being compared with those from previously published formulas, e.g., API Bul. 2N, Ponter et al., and Bruen & Vivatrat. In addition, ice pressures have been obtained with the approximate methods for a new uniaxial model that accounts for the stress-strain-strainrate behavior of sea ice, including its strain-softening behavior. The current emphasis is on the development of an orthotropic power law creep model for sea ice and its implementation within a finite element analysis framework to quantify the effect of material anisotropy on ice loads.

The key difference in the two approximate methods of analysis is that point stresses within the continuum can be obtained with the strain path method. As a result, local stresses at the ice-structure interface can be estimated, unlike the upper bound method which only yields the global pressure. However, both methods rely on an adequate specificiation of the velocity field in the ice sheet. This is obtained through a combination of theoretical modeling based on fluid mechanics and field ice movement survey data from an artificial island in the Beaufort Sea. In particular, two theoretical kinematic models are considered: one resulting from the superposition of a point source and a uniform flow (Kinematic Model A) that has been proposed by Bruen & Vivatrat; and the other resulting from the superposition of a doublet and a uniform flow (Kinematic Model B).

The results of the approximate methods indicate that:

(a) Kinematic Model B better models the ice movement survey data used here than Kinematic Model A.

(b) In the creeping mode of ice deformation, local ice pressures are of the same order of magnitude as the global pressures.

(c) Under the same conditions, Kinematic Model B, the API model, and the Ponter et al. model predict similar global pressures.

(d) The variation in global pressures for different power-law model parameters (Wang, Sanderson, Ting & Shyam Sunder) is on the order of 30%.

A key finding of the work is that for rate-dependent material models describing sea ice behavior, interface adfreeze and friction stresses can significantly influence both local and global ice pressures. The only realistic way to study these effects is through numerical models based on the finite element method of analysis.

This research has been summarized in a paper entitled "Sea Ice Indentation Accounting for Strain-Rate Variation", published in the proceedings of the ASCE Specialty Conference: ARCTIC '85 - Civil Engineering in the Arctic Offshore to be held at San Francisco, CA, March 25-27, 1985.

A finite element formulation for general viscoplastic behavior including creep (nonlinear viscoelasticity) has been developed and implemented in a computer code called DECNEC (Discrete Element Computational NEtwork Controller). A new bi-level solution algorithm has been developed for fast convergence in problems where permanent deformations dominate. This algorithm is based on a secant type iteration on the global equations of motion and a Newton-Raphson (tangent type) iteration, combined with an implicit numerical time integrator, on the rate-dependent constitutive relations at each integration point within an element. A post-processor, originally written at the Lawrence Livermore Laboratory, can be used in conjunction with the computer code to produce graphical displays. The program has the ability to simulate a free or frictional contact between two deformable bodies, i.e., no contact stresses due to adfreeze bond, by defining the interface as a "slideline". The current implementation is a two-dimensional version for plane stress problems. A four noded quadrilateral element is currently available. Although an eight-noded quadratic element is often preferred (and may be included in the future), accurate results can and have been obtained with the four-noded element using a finer finite element mesh. An isotropic power-law creep material model has been implemented in the present version of the program.

The accuracy of the computer code has been verified in two ways; through the solution of simple test problems, and by comparing the variability in predicted global pressures due to indenter diameter, material model parameters, and ice sheet velocity with that predicted by approximate methods of analysis. In both cases, the numerical solutions are accurate to within specified tolerances typically achievable in finite element analyses.

Numerical simulations have been performed under plane stress conditions to assess the influence of interface adfreeze and friction, material constants for a multi-axial power law creep model, grounded rubble pile, and ice sheet velocity on predicted global forces and local pressures. The results have been compared with those based on approximate methods of analysis. Stress, strainrate, and strain countours have been obtained in addition to the distribution of interface pressures.

The numerical simulations show that:

1. Global forces vary by a factor of 2.5 depending upon whether the interface condition is fixed (infinite adfreeze bond strength), roller, or free (no adfreeze bond strength or interface friction). The fixed condition is about 1.3 times and the free condition about 0.5 times the roller condition.

2. Finite element analysis predictions of global pressure differ from a modified form of the upper bound solution for Kinematic Model B by less than 10% for varying velocity, indenter diameter, and material constants. The modification is necessary since the two-dimensional nature of the kinematic models makes the approximate solutions strictly apply to plane strain conditions, and not to the plane stress condition of interest.
3. The ratio of maximum normal interface pressure to global pressure approximately varies in the range 0.35-1.10 depending upon the interface condition. It is 0.35 for the fixed condition, 0.55 for the roller condition, and 1.10 for the free condition.
4. The maximum (peak) normal interface pressures vary by a factor of 1.26 depending upon the interface condition. The fixed condition is about 0.83 times and the free condition about 1.04 times the roller condition. The maximum interface shear stress for the fixed condition is about 0.81 times the corresponding maximum normal pressure. However, a different boundary value problem involving a smaller contact area, as opposed to contact over half the perimeter in the free condition, will lead to higher interface pressures.
5. Pressure-area curves should be considered as providing the maximum normal interface pressure for a given indenter area of contact (form area), rather than the average integrated normal pressure over a tributary loaded area for a structural component. It is conservative to assume a uniform or rectangular distribution of the local pressure over the indenter area of contact for purposes of design.

6. Tensile stresses, strains and strainrates occur almost all over the ice sheet, and may be the key to explaining fracture behavior during indentation. While biaxial compression and tension states tend to occur for stress on the upstream and downstream sides, respectively, the state of strain is almost always compression-tension. The levels of tensile strain are often sufficient to cause cracking even before steady state creep is reached.

The possible effect of a grounded rubble pile or accreted ice foot on ice pressures was assessed by defining an effective indenter equal to a multiple (2.85) of the structural diameter. This resulted in a factor of 1.97 increase in global force. In the case of a grounded rubble pile, it would be over conservative to consider that all this force is transmitted to the foundation by the structure. On the other hand, the force transmitted to the foundation by the structure would decrease by a factor of 4.14 if both the structure and the grounded rubble pile could transmit a force proportional to the contact area of each with the foundation. This may be reasonable only if the rubble pile is consolidated and grounded fimly in the foundation soil such as in the case of constructed ice packs. Further research is necessary to quantify the level of force that can be directly transmitted to the foundation by a grounded rubble pile.

The numerical simulations also showed that (i) even a factor of two uncertainty in velocity will affect ice pressures only by about 20-30%, and (ii) uncertainties in material constants for an isotropic power law creep model may yield ice pressures that vary by about 15-30%. However, improved material models that include fracture and temperature effects in addition to the transversely isotropic behavior of sheet ice can have a major influence on ice pressure predictions.

This research has been summarized in a paper entitled "Sea Ice Indentation in the Creeping Mode", published in the proceedings of the 17th Annual Offshore Technology Conference, Houston, TX, May 6-9, 1985.

First-year columnar sea ice displays strong material anisotropy in a direction perpendicular to the plane of the ice sheet. Experiments have shown that the ratio of vertical to horizontal strength in the ice sheet lies in the range 2-5 for a wide range of strain rates. Plasticity type solutions based on approximate methods of analysis have shown this to have significant influence on global ice forces. The objective of current research is to postulate an orthotropic power law creep model accounting for material anisotropy, to calibrate it with available data, and to implement the model in the finite element analysis computer code DECNEC. The current solution algorithm is being extended to incorporate this new material model. The effect of material anisotropy (transverse isotropy) on <u>both</u> global forces and local pressures will then be quantified through numerical simulations. The results will be calibrated with those from approximate methods of analysis.

SEA ICE IDENTATION ACCOUNTING FOR FRACTURE

Field observations of sea ice identation on offshore structures in the Arctic show that fracture processes are a major factor in ice-structure interaction.

Fracture manifests itself in terms of tensile cracking and crushing in compression. Numerical simulations of ice-structure interaction processes in the creeping mode of deformation have indicated that the ice sheet consists of three regimes of principal stresses and strains; i.e., compression-

compression, compression-tension, and tension-tension. The latter two regimes occupy a major fraction of the area of the continuum. Since ice is weaker in tension than in compression once cracks occur, accounting for the differing behavior of ice in tension may help to reduce (or limit) ice force predictions significantly.

A new constitutive model for sea ice, applicable to monotonic uniaxial loading in both compression and tension, has been proposed and calibrated with experimental data. The stress-strain-strainrate behavior of sea ice has been modelled accounting for strain softening and for fracture which manifests itself in terms of tensile cracking and crushing in compression. The adequacy of the model has been demonstrated by comparison with experimental data obtained under constant strainrate, creep, and constant stressrate conditions. The model has been used to predict the occurrence of first cracks in ice under uniaxial compressive loading. Tensile strains occur under this loading condition as a result of the Poisson effect and/or incompressibility condition. Once cracks occur, the material continues to sustain compressive load but loses its ability to carry tensile loads in the transverse direction if applied. This is a realistic assumption and has been used often in modeling concrete behavior. A limiting tensile strain criterion dependent on the instantaneous strainrate in tension has been used to predict crack nucleation. The results for compressive creep compare very well with the experimental data of Gold.

This research has been summarized in a paper entitled "Ductile to Brittle Transition in Sea Ice Under Uniaxial Loading" to be published in the proceedings of the 8th International Conference on Port and Ocean Engineering under Arctic Conditions, Greenland, September 7-14, 1985.

Prior to implementing the model within a finite element analysis framework to predict ice forces and pressures, it is necessary to extend the model to (i) identify the recoverable (instantaneous and delayed elastic) and permanent (viscous) components of strain, (ii) account for unloading/reloading conditions, and (iii) account for multiaxial effects. This is the focus of current research. The initial emphasis is on obtaining a constitutive model adequate to characterize sea ice indentation under plane stress conditions.

The quantification of fracture behavior requires two criteria, one for initiation and the other for propagation. Fracture initiation can often be well described by a stress or strain criterion. However, two alternative approaches are available to describe fracture propagation: a tensile limiting strain or strength criterion, and a fracture mechanics criterion based on a pre-existing distribution of cracks in the continuum. The former approach for fracture propagation can be used to model fracture behavior in a material originally in virgin (flawless) form.

In the case when ice is a load <u>bearing</u> system, a fracture mechanics criterion for cracking is conservative. However, when ice features act as load <u>transmitting</u> systems, a fracture mechanics approach may lead to unconservative results. To account for tensile cracking and compressive fracture in ice and still be conservative in force and pressure predictions, a rate-dependent limiting strain or stress criterion is preferable to the fracture mechanics approach. The former criterion is adopted in this project.

Several approaches are available to account for cracking in a finite element framework. Two of the more common approaches are the discrete cracking models which follow individual discrete cracks between elements and the smeared cracking models which treat the gross (smeared) effect of cracks in an element. The latter approach has been preferred in finite element analyses of concrete since it is computationally far more convenient, and will be adopted in this project. An added advantage is that smeared crack models can be extended easily to allow for an objective energy release rate criterion for fracture propagation. The resulting theory, called the blunt crack band theory, will require the development of an appropriate modification to the rate-dependent limiting tensile stress fracture criterion.

A major research effort is being undertaken to (1) extend the plane stress finite element analysis computer code to incorporate smeared cracking models, and (2) implement the constitutive model in the program. The influence of fracture on both global forces and local pressure will then be quantified through numerical simulations.

3. NOTABLE NON-TECHNICAL ACTIVITIES

PUBLISHED OR SUBMITTED PAPERS

1. Ting, S-K., and Shyam Sunder,, S., "Sea Ice Indentation Accounting for Strain-Rate Variation," Proceedings of the ASCE Specialty Conference: ARCTIC '85 - Civil Engineering in the Arctic Offshore, San Francisco, CA, March 25-27, 1985, pp. 931-941.

2. Chehayeb, F.S., Ting, S-K., Shyam Sunder, S., and Connor, J.J., "Sea Ice Indentation in the Creeping Mode," Proceedings of the 17th Annual Offshore Technology Conference, Houston, TX, May 6-9, 1985, OTC Paper 5056, pp. 329-341. Paper to be simultaneously reviewed for publication in the Journal of Engineering Mechanics, ASCE.

3. Shyam Sunder, S., and Ting, S-K., "Ductile to Brittle Transition in Sea Ice Under Uniaxial Loading," Proceedings of the 8th International Conference on Port and Ocean Engineering Under Arctic Conditions, Narssarssuaq, Greenland, September 6-13, 1985. Expanded version of paper to be submitted for publication in Cold Regions Science and Technology.

4. Shyam Sunder, S., Ganguly, J., and Chehayeb, F.S., "Anisotropic Sea Ice Indentation in the Creeping Mode," Tentatively scheduled for presentation at the 5th International Offshore Mechanics and Artic Engineering Symposium, Tokyo, Japan, April 13-18, 1986 based on review of abstract. Paper in preparation for final review and acceptance, June 1985.

SEMINARS AND TALKS

1. Both Professors S. Shyam Sunder and Jerome J. Connor participated in the Workshop on Breaking Process of Ice Plates held at M.I.T. on November 1-2, 1984. The title of their presentations are listed below:

   a. Professor S. Shyam Sunder: Sea Ice Indentation Accounting for Strain-Rate Variation.

   b. Professor Jerome J. Connor: Numerical Simulation of the Creep Mode in Ice-Structure Interaction.

   Professor S. Shyam Sunder was invited to talk on the same topic at the weekly seminar of the Constructed Facilities Division of the Department of Civil Engineering at MIT on December 5, 1984.

2. Professor S. Shyam Sunder was invited to talk on "Sea Ice and Its Mechanical Behavior" at a series of seminars on Engineering in the Arctic organized during MIT's Independent Activities Period, January 1985.

PROFESSIONAL ACTIVITIES

1. Professor S. Shyam Sunder was a member of the Conference Committee for ARCTIC '85 - Civil Engineering in the Arctic Offshore Speciality Conference of the ASCE held in San Francisco, March 25-27, 1985. He was also moderator for a session on Probabilistic Methods in Arctic Offshore Engineering.
2. Professor S. Shyam Sunder is Chairman of ASCE's Subcommittee on Arctic and Frontier Regions. This subcommittee operates under the ASCE Structural Division's Committee on Reliability of Offshore Structures. This Committee met at San Francisco in conjunction with item 3.
3. Professor S. Shyam Sunder has been appointed Vice-Chairman of the ASCE Task Committee on Reliability-Based Techniques for Designing Offshore Arctic Structures which is entrusted with the responsibility of producing a monograph bearing the same name. He attended the Task Committee meetings at San Francisco (March 1985) and Houston (May 1985).
4. Professor S. Shyam Sunder attended the Arctic Energy Technologies Workshop organized by the U.S. Department of Energy as part of a recently initiated Arctic and Offshore Research Program. The workshop was held at Morgantown, West Virginia, on November 14-15, 1984. He also participated in the discussion group on Arctic Offshore Structures which had the task of defining the state-of-the-art, identifying technical issues, listing research and development needs, and recommending topics for research support by the U.S. DOE.

5. Professor S. Shyam Sunder participated in a workshop on "Northern Research Needs in Civil Engineering" organized by the University of Alaska, Fairbanks, in Seattle, WA, February 16-17, 1985. The workshop was sponsored by the National Science Foundation to help formulate a five year plan for Arctic research under its mandate for implementing the Arctic Research & Policy Act of 1984. Professor Shyam Sunder contributed to the Committee on Offshore and Coastal Facilities, Design and Construction.

6. Professor Jerome J. Connor is leading the organization of an International Conference on Ice Technology (ITC '96) to be held at MIT, June 10-12, 1986. An international Scientific Advisory Committee has been set up with Professor Connor and Dr. C.A. Brebbia of Southampton University, England, as Co-Chairmen. This conference will be sponsored by the Center for Scientific Excellence in Offshore Engineering at MIT, the Centre for Advanced Engineering Studies at the University of Southampton, and the MIT Sea Grant Program.

7. Professor S. Shyam Sunder attended a meeting of the Ice Mechanics Committee of ASME's Offshore Mechanics and Arctic Engineering Division of which he is a member at Dallas, TX in February 1985.

8. Professor S. Shyam Sunder attended a meeting of ASCE's Committee on Reliability of Offshore Structures of which he is a member at Houston, TX in May 1985.

9. Professor S. Shyam Sunder has been invited to serve as a member of the Conference Committee for POAC '87, the 9th International Conference on Port and Ocean Engineering under Arctic Conditions. He is organizing technical sessions on Numerical Modeling of Ice-Structure Interaction and Probabilistic Methods in Arctic Offshore Engineering.

EXPERIMENTAL DATA FROM U.S. ARMY CRREL:

An informal agreement has been reached with the U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., Group under the leadership of Dr. Gordon Cox concerning our use of experimental data obtained by them. Under this agreement we can have immediate access to all their experimental data, although any publication by us of their data would in general be dated after they have had an opportunity to publish the results themselves.

4. BUDGET

The total expenditure as of May 31, 1985 is $42,195.27. This reflects expenditures for the nine month period September 1, 1984 (the requested project starting date) through the end of May.

Professor S. Shyam Sunder charged 10% of his salary to the project and 20% to the SOHIO account through January 31, 1985. From February 1, 1985 he charged 20% of his salary to the MMS account, and an equal amount to the SOHIO account. He is charging 0.8 of a month's salary to the account in the Summer, and 1.2 months to the SOHIO account. Professor Jerome J. Connor charged 10% of his salary to the MMS account and 10% to the SOHIO account through May 31, 1985, i.e., the academic year.

Mr. S-K Ting and Mr. F.S. Chehayeb were full-time Research Assistants on the project from September 1, 1984 through May 31, 1985. During the Fall Term their salary was charged to the SOHIO account, while during the Spring Term their salary was charged to the MMS account. In the Summer (6/1/85-8/31/85), Mr. S-K Ting and Mr. Jaideep Ganguly are full-time Research Assistants on the project. Their salary is being charged to the SOHIO account.